

# Additive Manufacturing Overview: Propulsion Applications, Design for and Lessons Learned

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AIAA JPC

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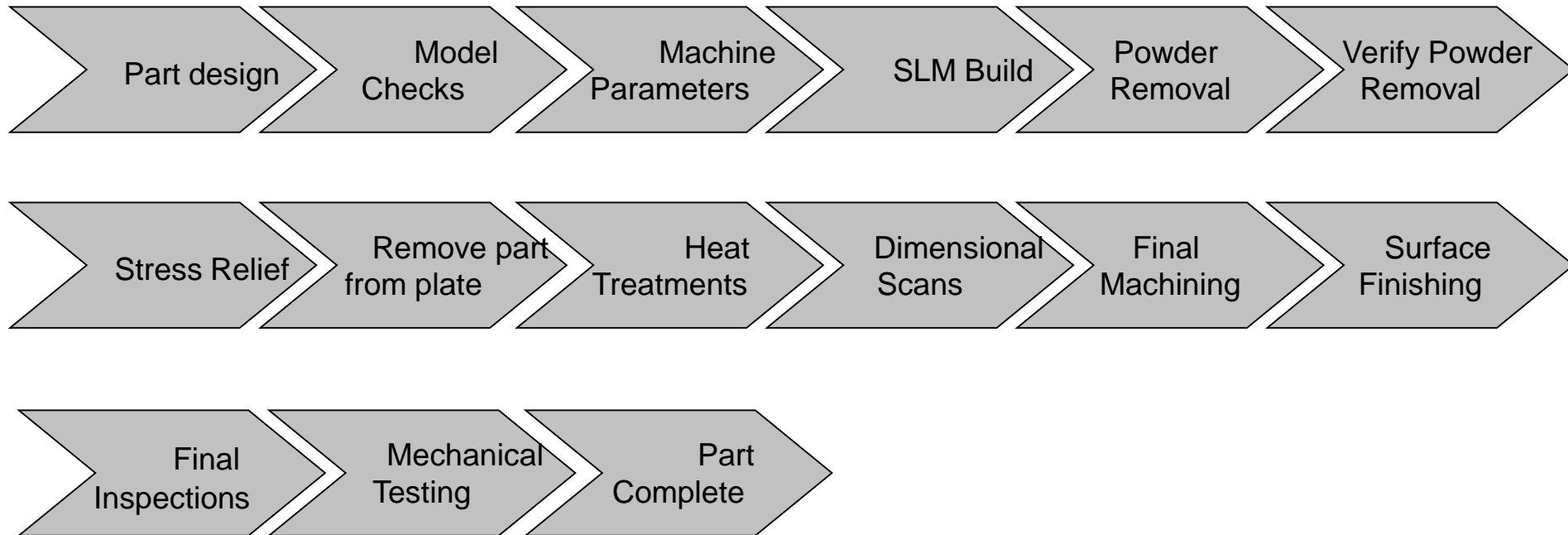
National Aeronautics and  
Space Administration



**MARSHALL**  
SPACE FLIGHT CENTER



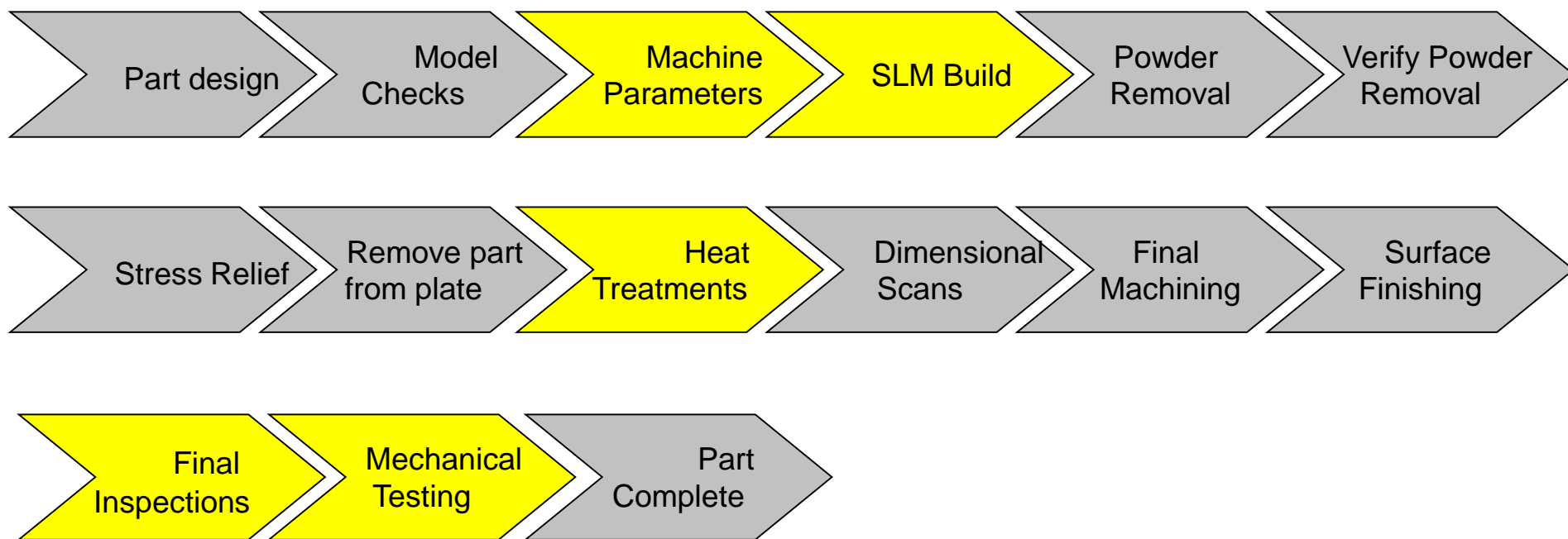
# Actual Process Flow



Each process step also includes a series of additional tasks in order to properly design, build, or complete post-processing



# Key Steps in AM *Process* Qualification

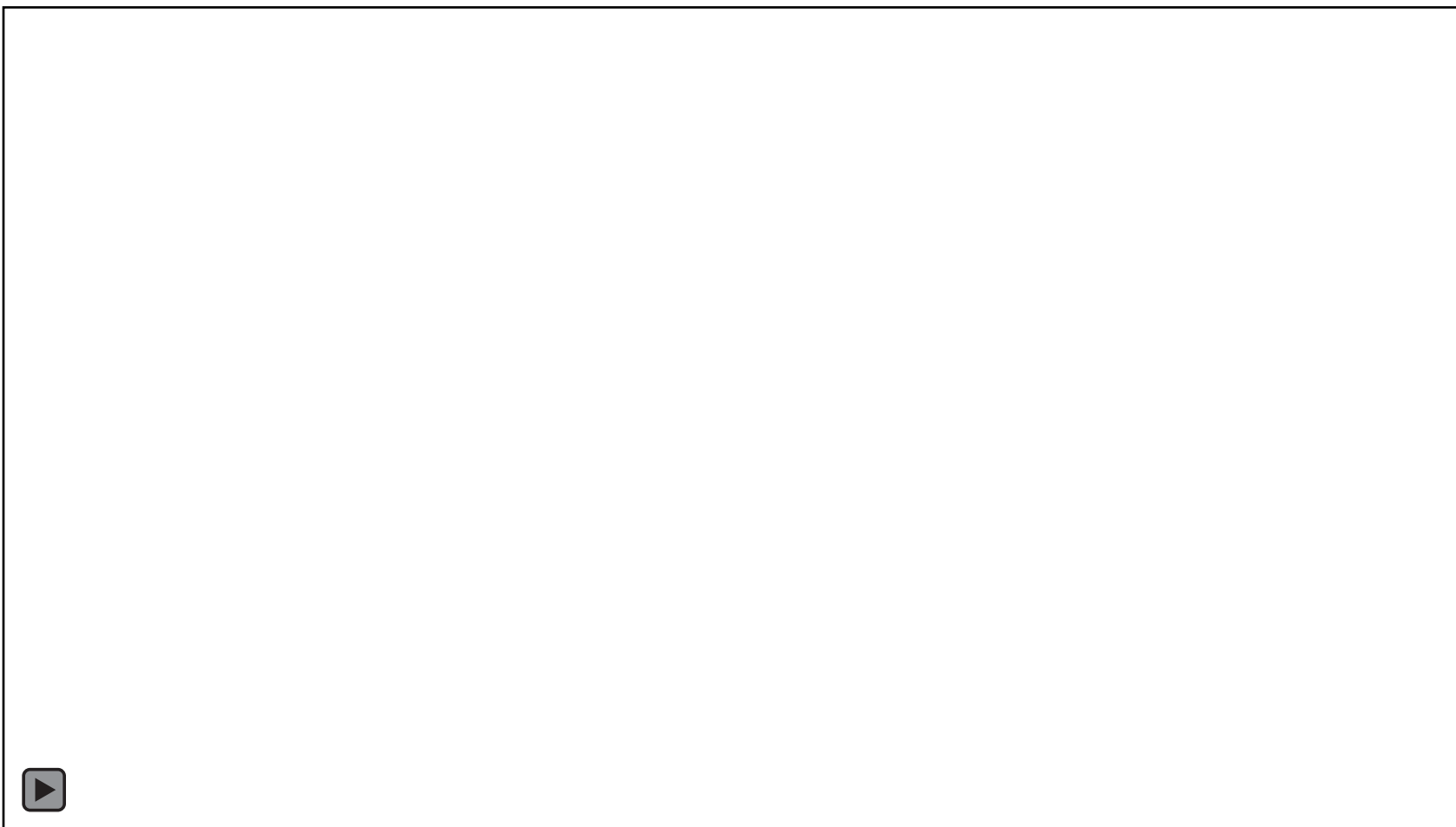


An AM part is only as good as its AM process.  
And any process is only as good as its weakest link.



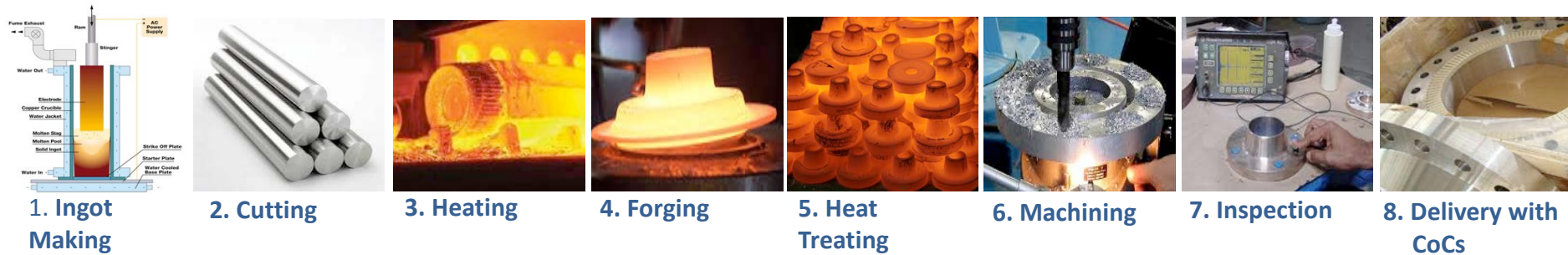
# The SLM Process

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*AM machines create a unique material product form – typically, the purview of the foundry or mill and guaranteed through CoCs based on proprietary process controls and commercially-available specifications (e.g. ASME, SAE, ANSI, ASTM, AWS, MIL specs).*

## Subtractive Forging Process

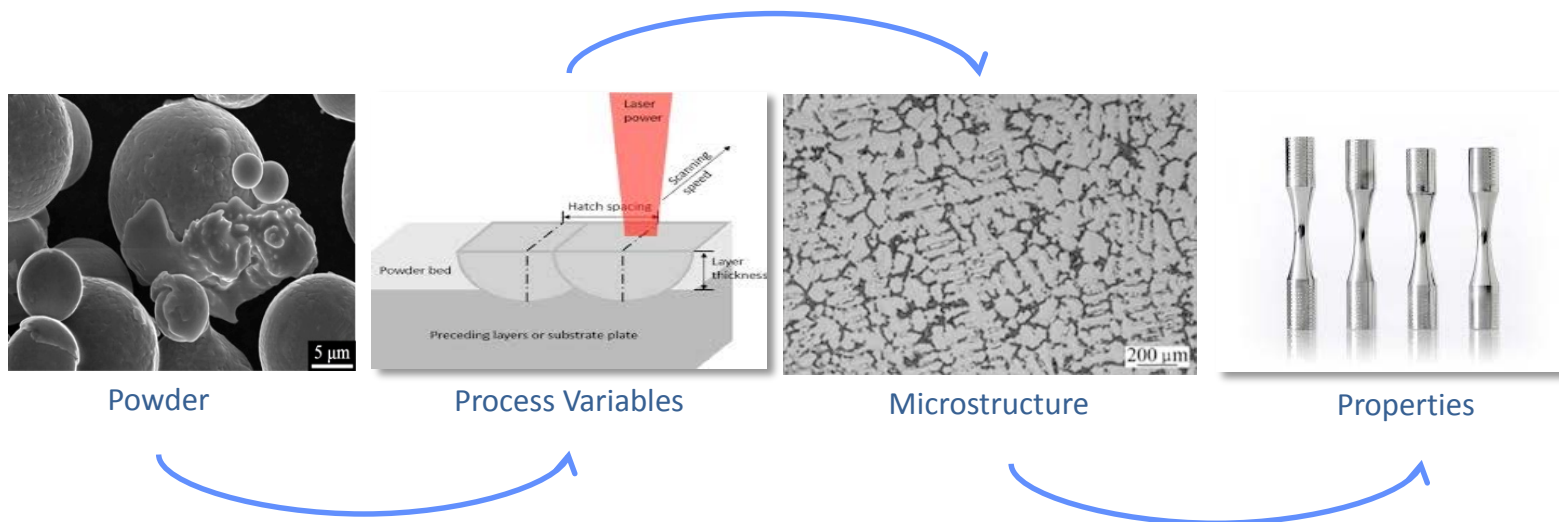


## Additive SLM Process





- As a unique material product form, the AM metallurgical process must be qualified on ***each and every*** individual AM machine for critical flight parts.
- Process controls are ensured by in-house Quality Controls and audited by responsible Material and Quality Assurance organizations.



**LASER**  
Innovation group

2

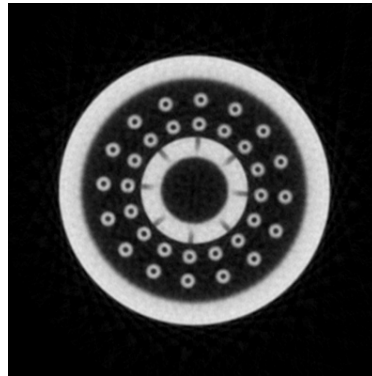




- Due to significant reliance on process controls for the reliability of the product, AM processes are “Complex” per NASA-NPD-8730.5.
- Quality Assurance is fundamental to the adoption and execution of AM.



Metallurgical  
Process  
Control



Part  
Process  
Control



Equipment, Facility,  
and Training  
Controls

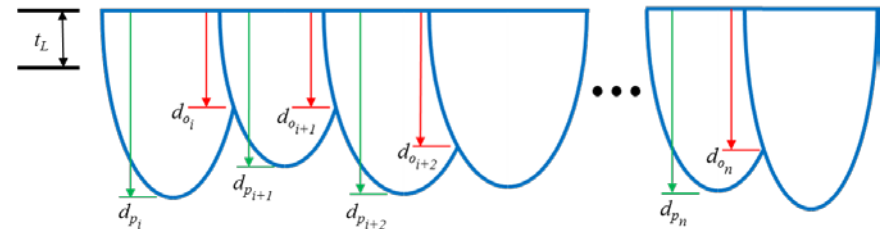
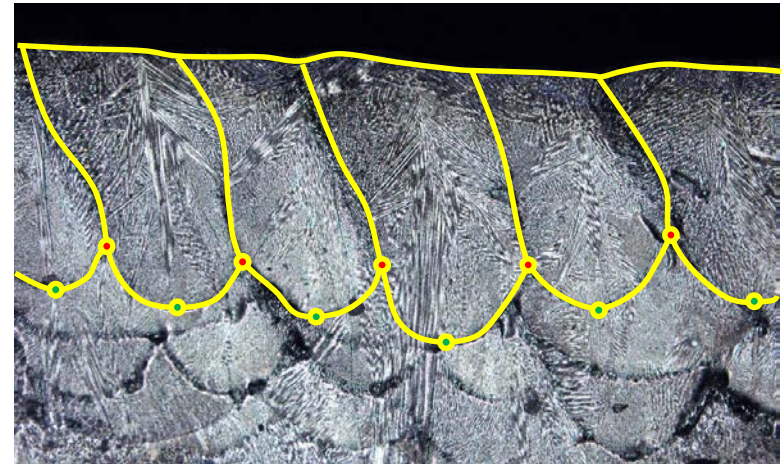


Quality  
Management  
System

Each control has an essential role in the qualification of AM processes and parts and certification of the systems in which they operate.



- Laser Powder Bed Fusion (L-PBF)  
Metallurgical Process Qualification
  - Definition of a candidate metallurgical process
    - Powder feedstock specification
    - Fusion controls (L-PBF machine parameters and operating conditions)
    - Thermal processes (heat treating)
  - Metrics for the qualification of a candidate metallurgical process
    - Density
    - Microstructural quality
    - Tolerance to process variations
    - Surface texture and detail rendering
    - Mechanical properties





As-Built

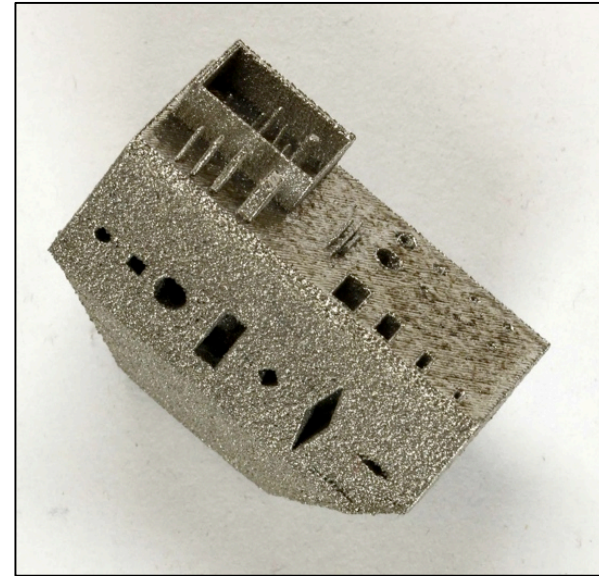
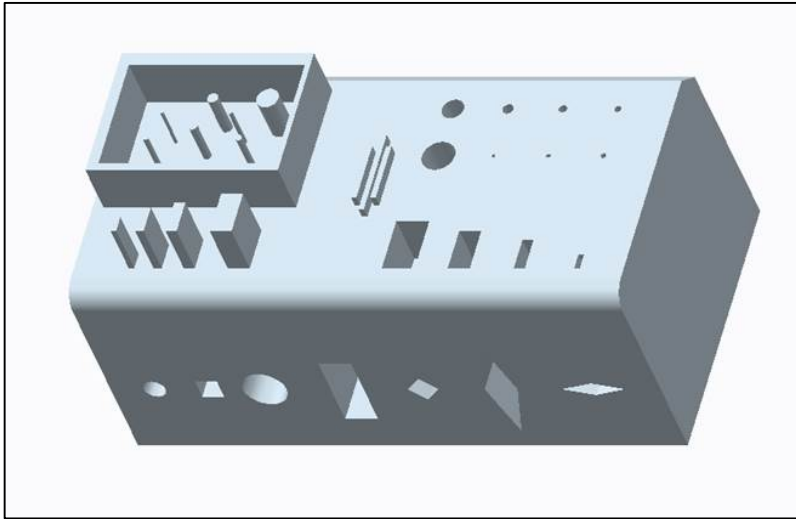


Stress-Relieved



HIPed & Final Condition

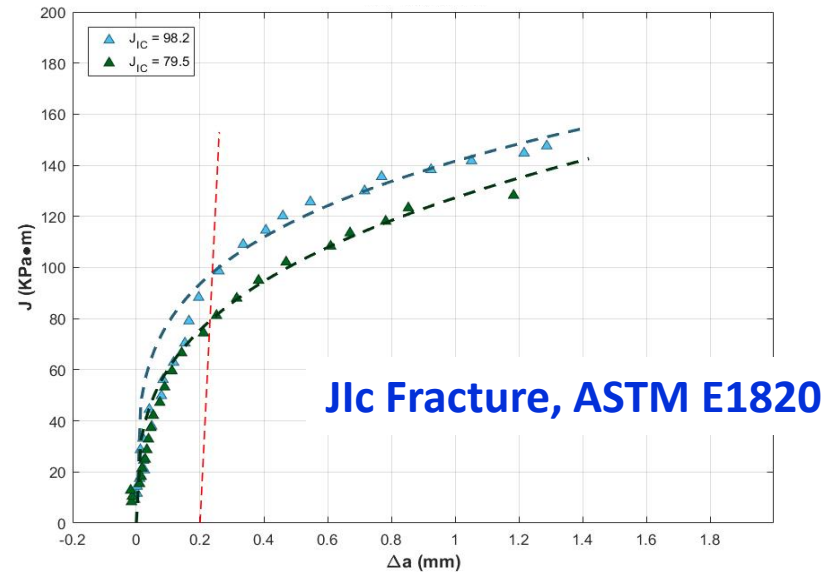
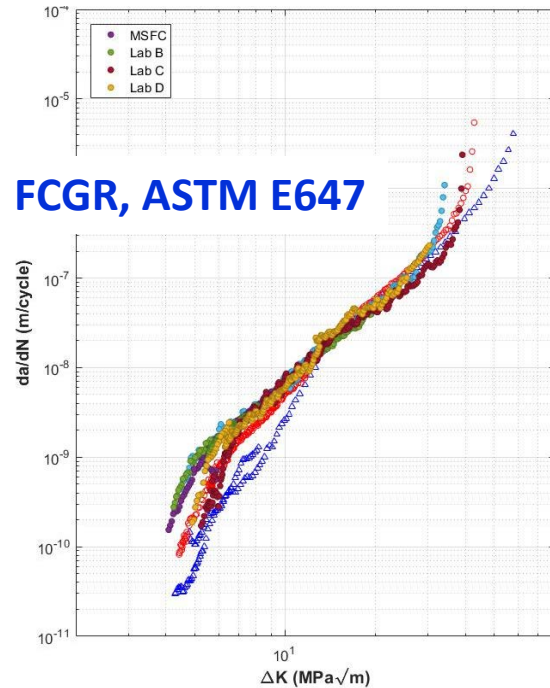
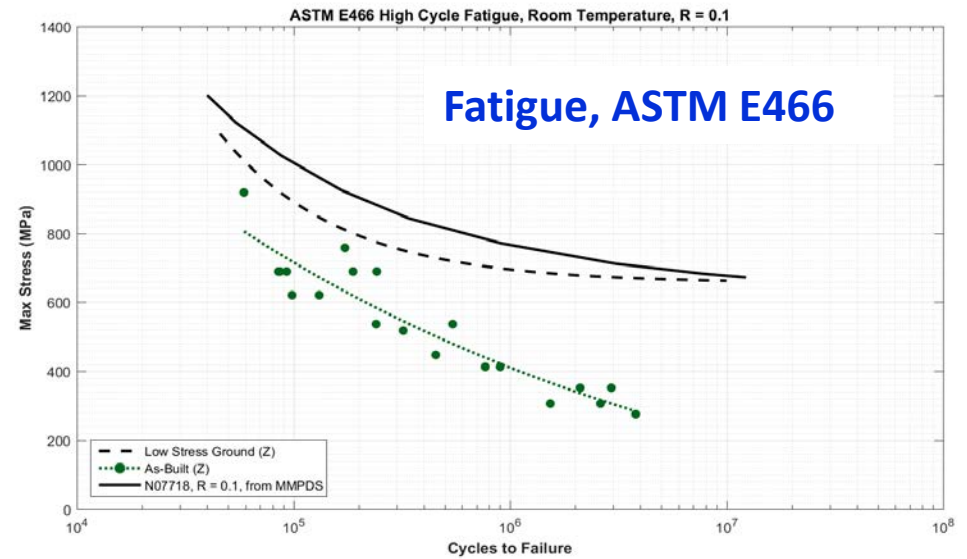
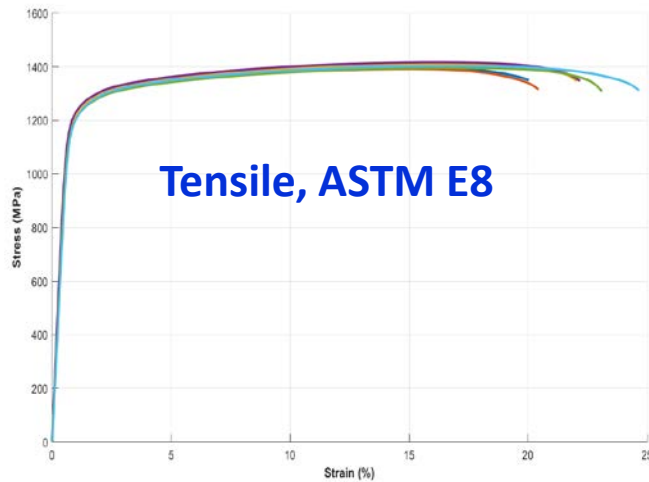
- Demonstrated repeatability and acceptability
  - As-built densification, microstructure, and defect state
  - Thermal process for controlled microstructural evolution



- Reference parts
  - Metrics for surface texture quality and detail rendering.
  - Provides standard assessment of overhanging, vertical and horizontal surface texture, acuity of feature shape and sizes.



# Metric: Material Properties







# HCF Performance directly related to Surface Finish



Fatigue life decreases with increasing surface roughness.



Low stress ground



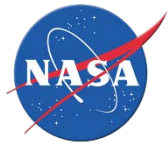
As-built



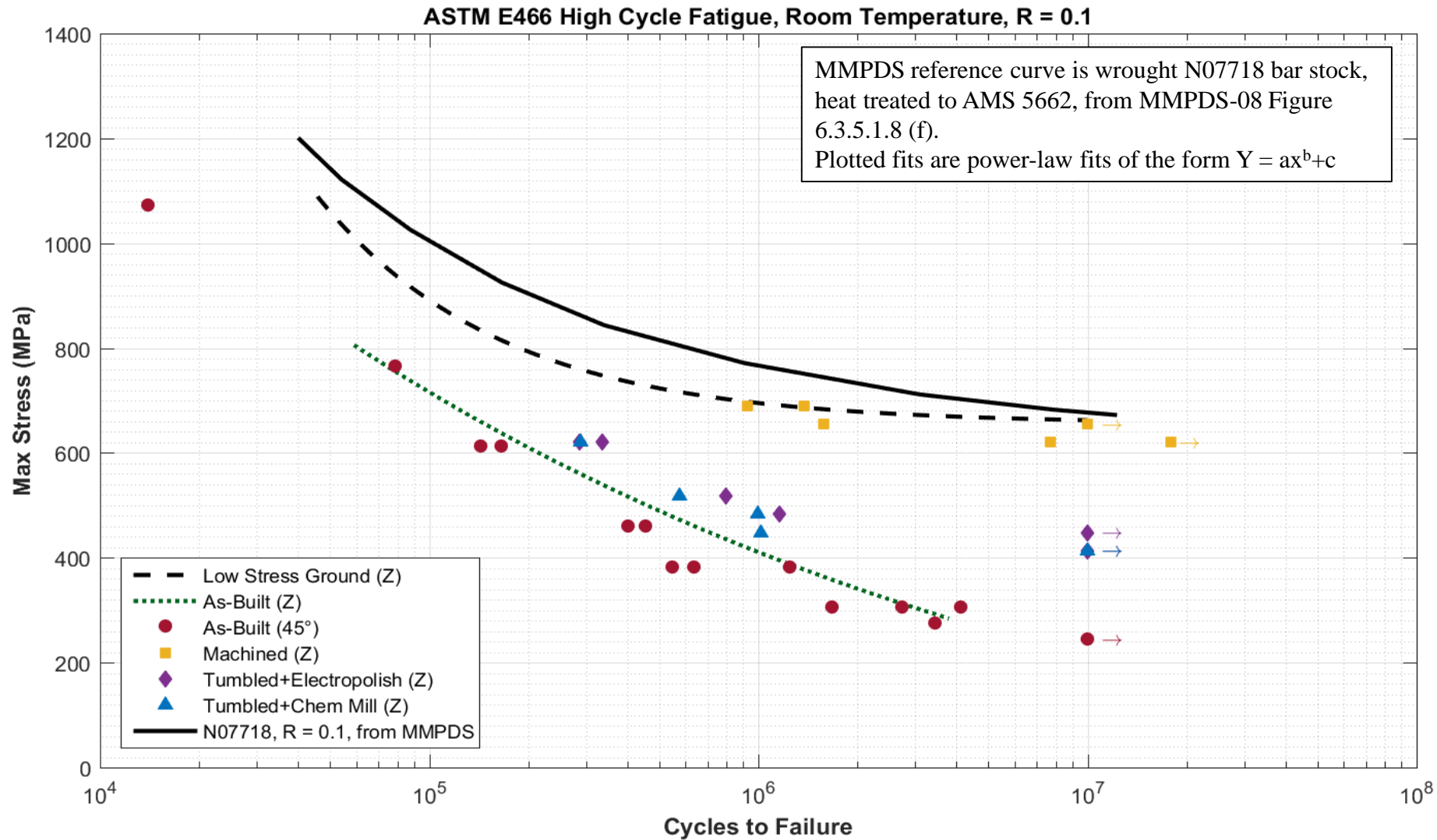
Tumbled & Electropolished



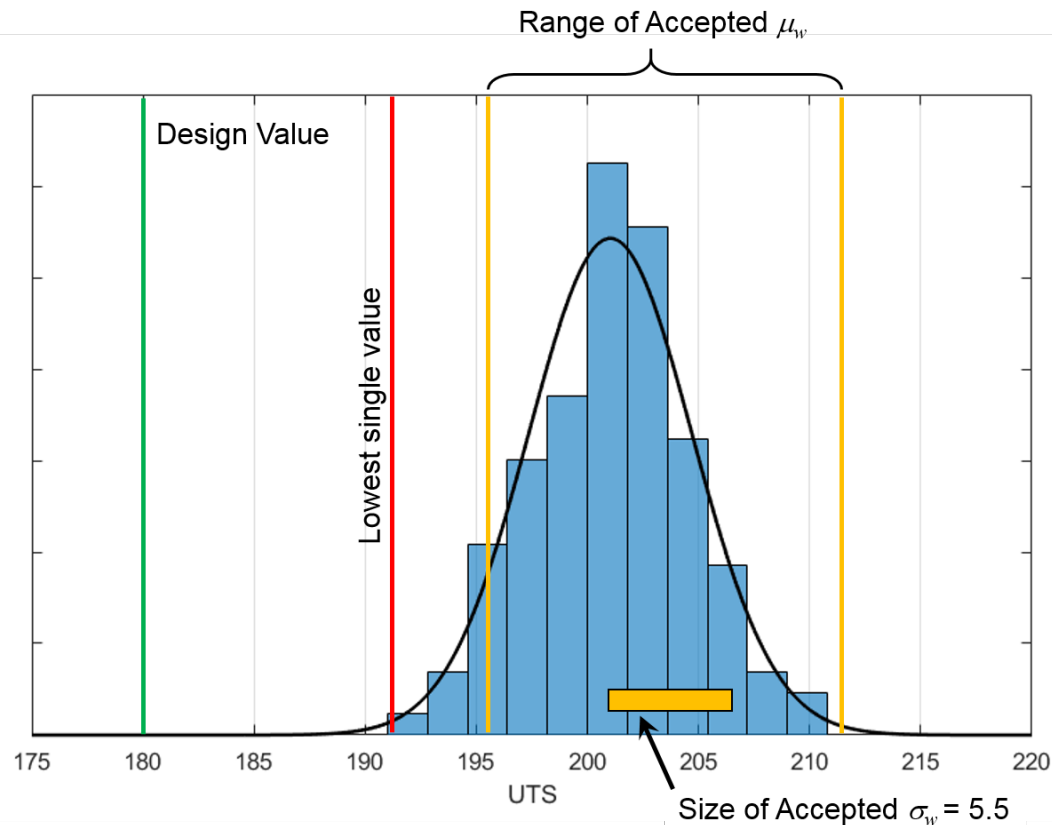
Tumbled & Chem Milled



# HCF of SLM 718 with varying Surface Conditions



- NASA provides requirements for material properties and related Statistical Process Control (SPC) criteria.
  - Material properties are tracked continuously and used to set witness test acceptance criteria.
  - SPC maintains process under control and maintains coherence between process capability and assumed design properties.

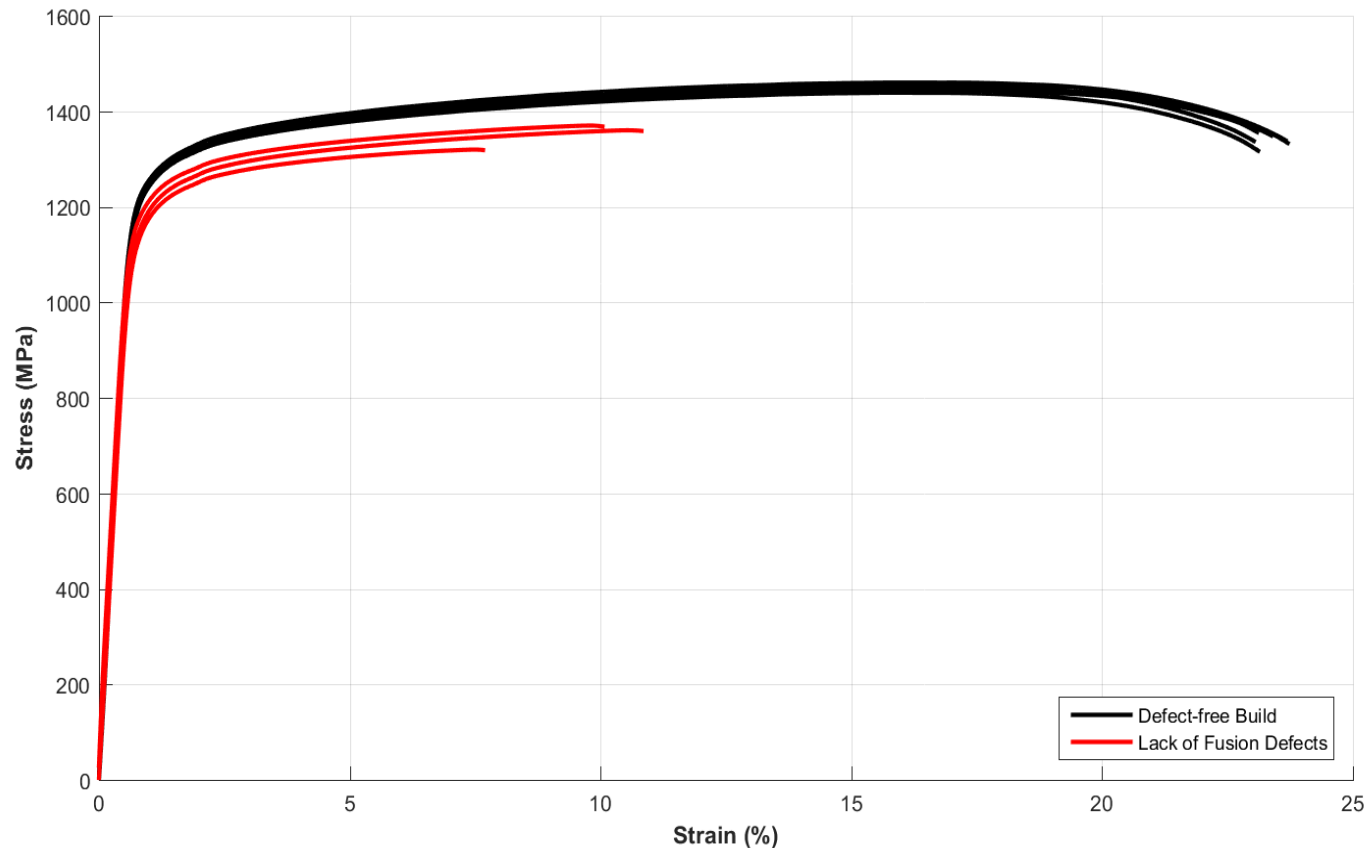




# Lesson Learned: SLM 718 Defective Build



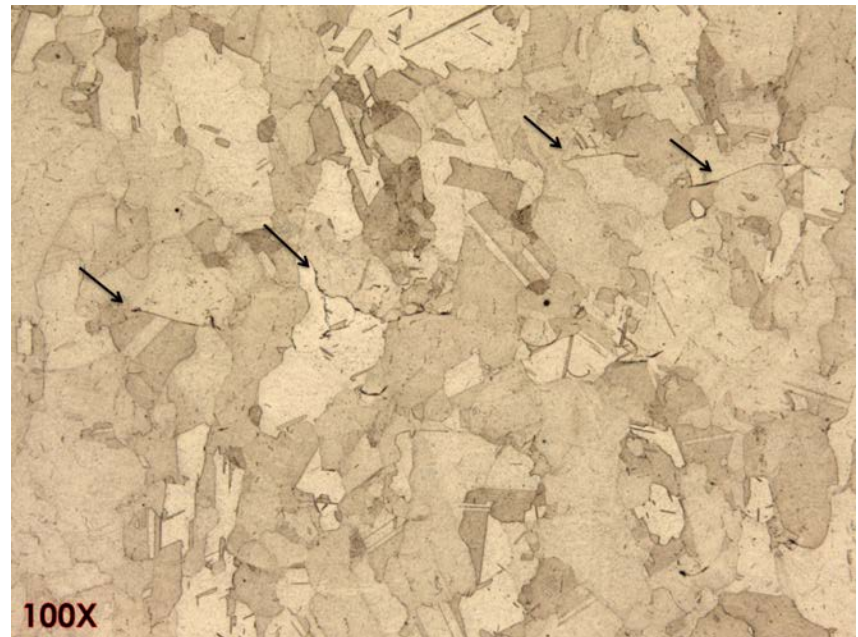
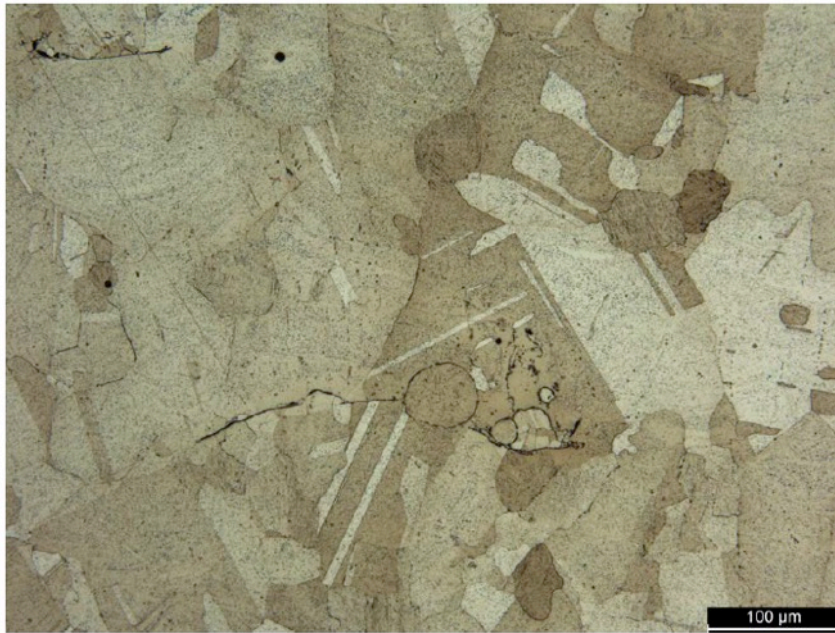
- A build of test specimens was produced; all indications were that the build was successful.
- Witness tensile testing revealed lower than expected material properties.







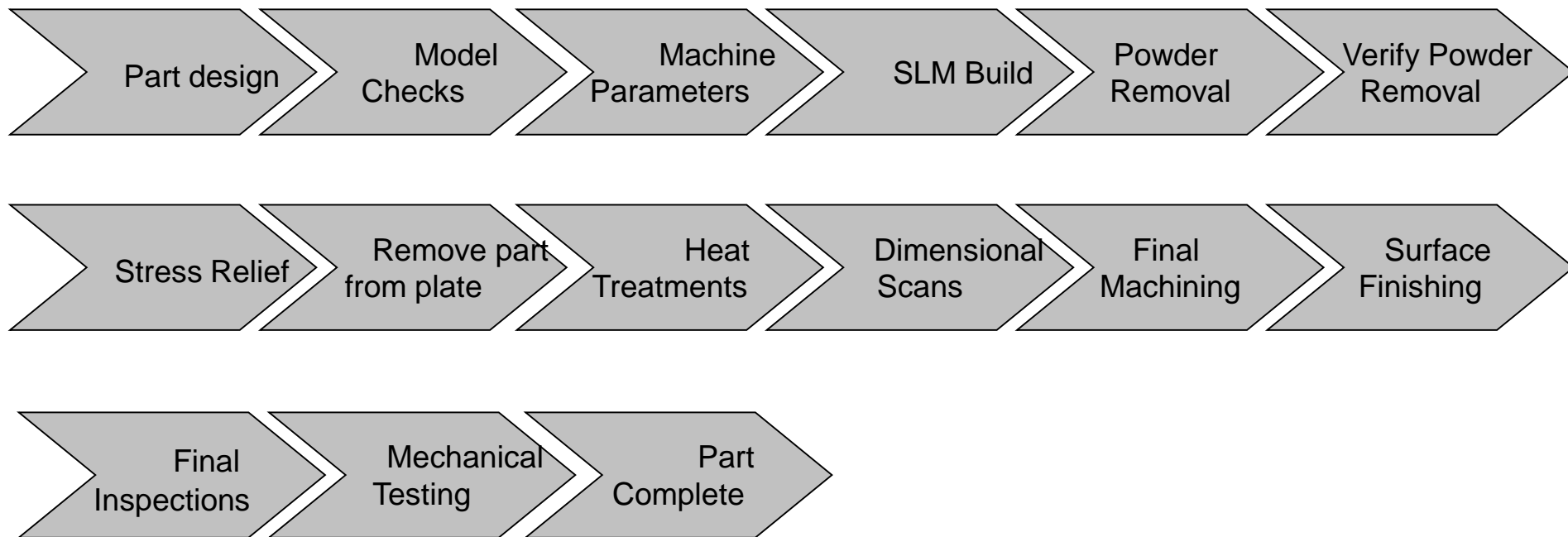
# Lesson Learned: SLM 718 Defective Build



- Metallographic examination revealed lack of fusion defects in the material.
- Source determined to be a clogged ventilation duct that caused attenuation of the laser, which allowed combustion by-products to settle on the powder bed.



# Part Process Flow



Each process step also includes a series of additional tasks in order to properly design, build, or complete post-processing

- Part Production Controls employ the foundational controls and classic engineering processes to produce quality AM hardware.
- NASA provides requirements for
  - The AM design process
  - Part classification
  - Part production plans
  - Pre-production articles
  - Manufacturing readiness reviews
  - Qualified Part Process
  - Production Engineering Controls
  - Acceptance procedures
- Validation and verification of these requirements are captured in a Part Production Plan (PPP) and Production Records.



CCP SuperDraco LAS Thrust Chamber



# Part Production Controls



- As the part design matures, Part Production Plans (PPPs) provide insight.
- Only part-specific product requiring NASA approval.
- Typical PPP Content:
  - Drawing number and part name
  - Part synopsis, providing a brief summary of the purpose of the part in context to the system, the operational environments (temperatures, fluids), and CAD model views to illustrate the part and key features
  - Material
    - Identification of the QMP specified for production, and Identification of MPS used for assessment
  - Part classification with summary rationale for consequence of failure, structural demand, and AM risk
  - Summary of the integrated integrity rationale for the part
    - Describe all non-destructive testing and the degree of coverage or any limitations
    - Describe all proof test operations, including role in integrity rationale, method of analysis, and coverage or limitations
  - List of required witness tests, witness articles, and associated acceptance requirements
  - Illustration of the complete build with part orientation, location, and witness specimens
  - Summary list or table with all production steps in sequence as governed by the Production Engineering Record
    - Include all key operations such as build, powder removal, as-built inspection, support removal, platform removal, heat treating, cleaning, welding, machining, surface treatments, NDE steps, proof test.
  - Description of any specific controls required for post-build part processing operations that are process-sensitive, i.e. outcome of the operation is difficult to verify but critical to the part
  - Pre-production article requirements, or reference to a separate plan
  - Names of configuration-controlled electronic files (and their hashes) needed for the part
  - List of references supporting the PPP (analysis reports, fracture control reports, etc.)
  - Complete list of all required part acceptance certificate of compliance information.
    - Dimensional inspection report, NDE reports, powder lot, build logs, etc,



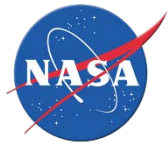


## Part Production Controls

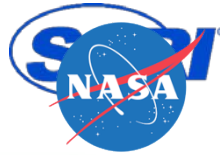
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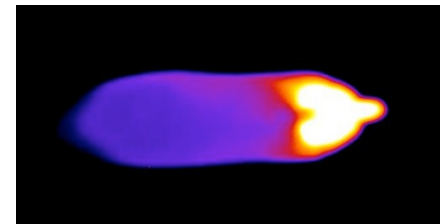
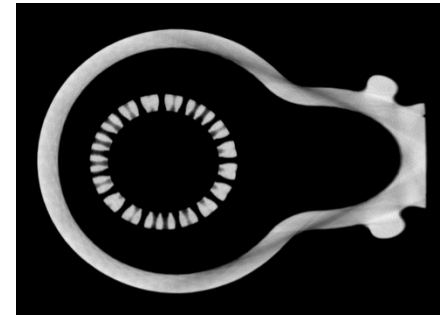
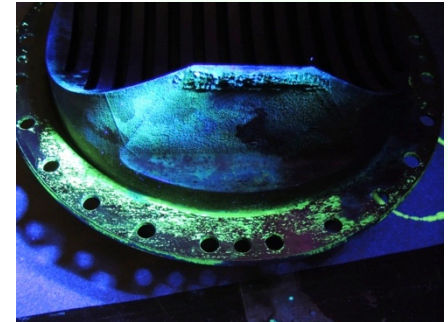
- Successful pre-production article evaluation and manufacturing readiness review (MRR) generates a Qualified Part Process (QPP).
- Critical step in quality assurance of AM production builds.
  - Formal and rigorous
  - Special significance at AM process vendors
  - Complete definition for entire part production process
  - Locked configurations and build controls
  - Includes all digital product definitions
  - Any change to QPP requires re-qualification review



# A Note on Inspections



- Traditional NDI techniques ineffective for SLM features such as as-built surfaces, blind internal passages, grain structure, and high density.
- CT is beneficial in detecting trapped powder before HIPing and final heat treatments.
- X-ray inspections remain the preferred technique for detecting internal flaws and CIF sizes.
- “Open-loop” in-situ processing presents opportunities for identifying defects during the layer-by-layer AM build.
- “Closed-loop” in-situ detection methods are in active development.
- ASTM E07 Subcommittee on Nondestructive Testing is a valuable resource.





# Equipment, Facility, and Training Controls

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- NASA provides requirements for control and qualification of equipment, facility, and trained personnel.
- Equipment and Facility Control
  - Qualification
  - Calibration
  - Maintenance
  - Contamination control
  - Facility safety (e.g., powder handling)
- Personnel Training
  - Dedicated training in equipment and engaging quality assurance
  - Operator certifications required, tiered based upon responsibility



# Quality Assurance Integration

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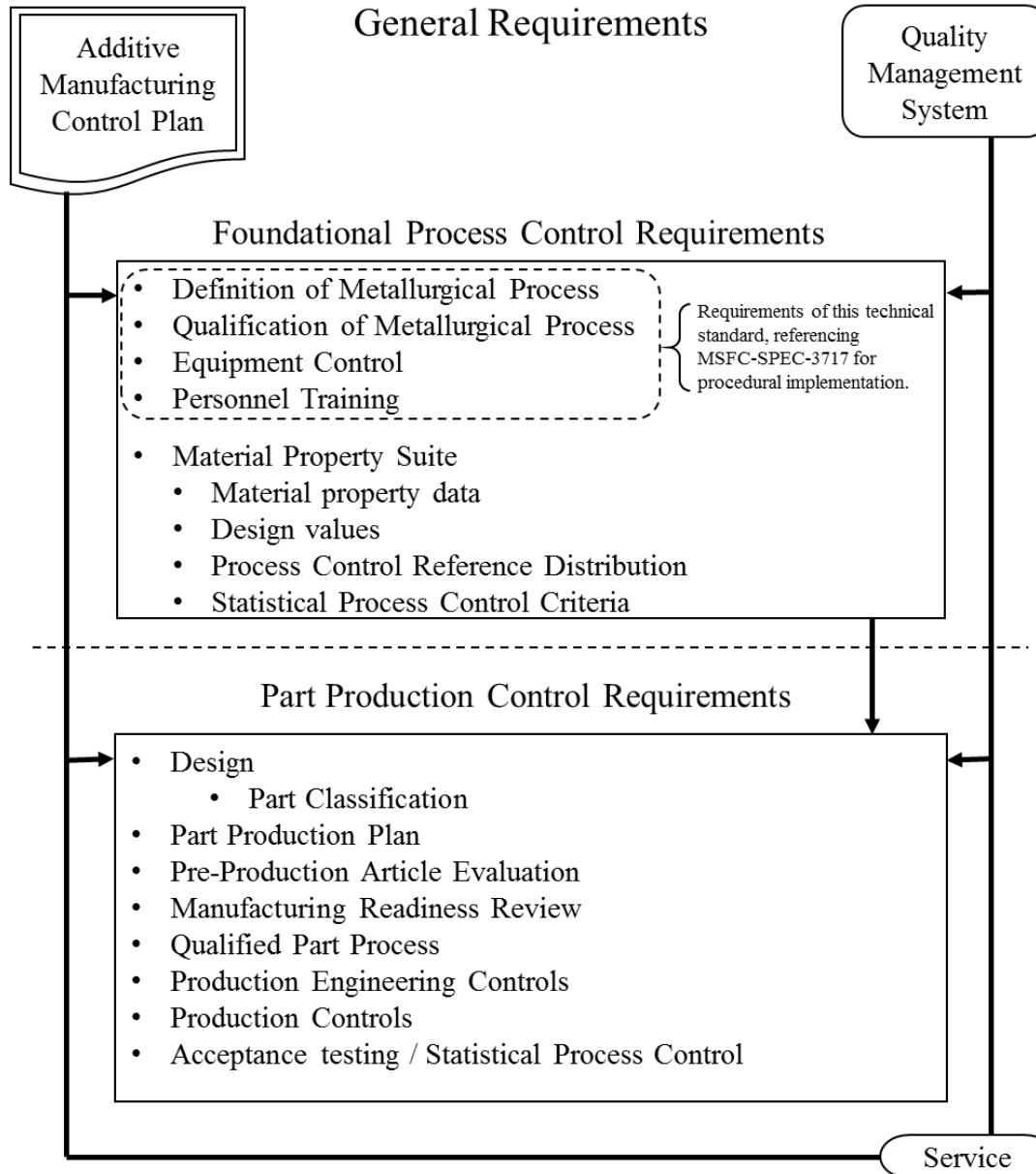


- Quality Management System required
  - AS9100 registration, or an equivalent
  - Engaged at all entities involved in design and production of AM hardware
- Additive Manufacturing Control Plan (AMCP)
  - Describes how the AM process will be implemented, including all aspects of quality assurance
  - NASA-approved document
  - Documents tailoring of requirements





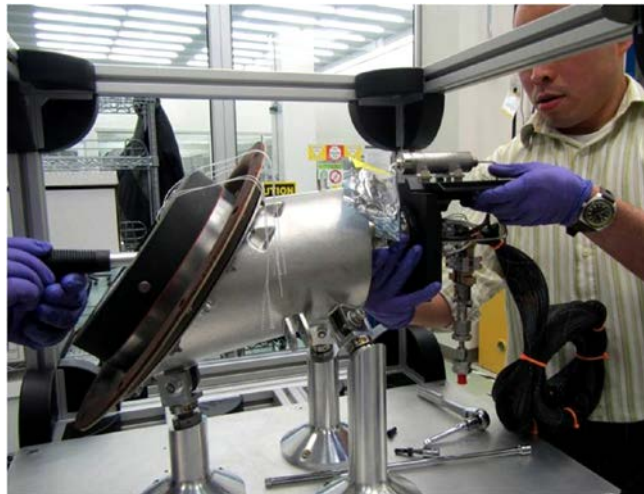
# General NASA Requirements



- NASA is leading in the integration of **critical** AM parts into human-rated flight systems.
  - Commercial Crew Program
  - Orion Crew Module
  - Space Launch System
- Due to significant reliance on process controls for the reliability of the product, AM processes are “Complex” per NASA-NPD-8730.5.
- Quality Assurance is fundamental to the execution of AM.



CCP - SpaceX



Orion – Aerojet Rocketdyne



SLS - Aerojet Rocketdyne





National Aeronautics and  
Space Administration

NOT  
MEASUREMENT  
SENSITIVE

**MSFC-STD-3716**  
REVISION: DRAFT 1  
EFFECTIVE DATE: Not Released

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George C. Marshall Space Flight Center  
Marshall Space Flight Center, Alabama 35812

**EM20**  
**MSFC TECHNICAL STANDARD**

**Standard for Additively Manufactured Spaceflight  
Hardware by Laser Powder Bed Fusion in Metals**

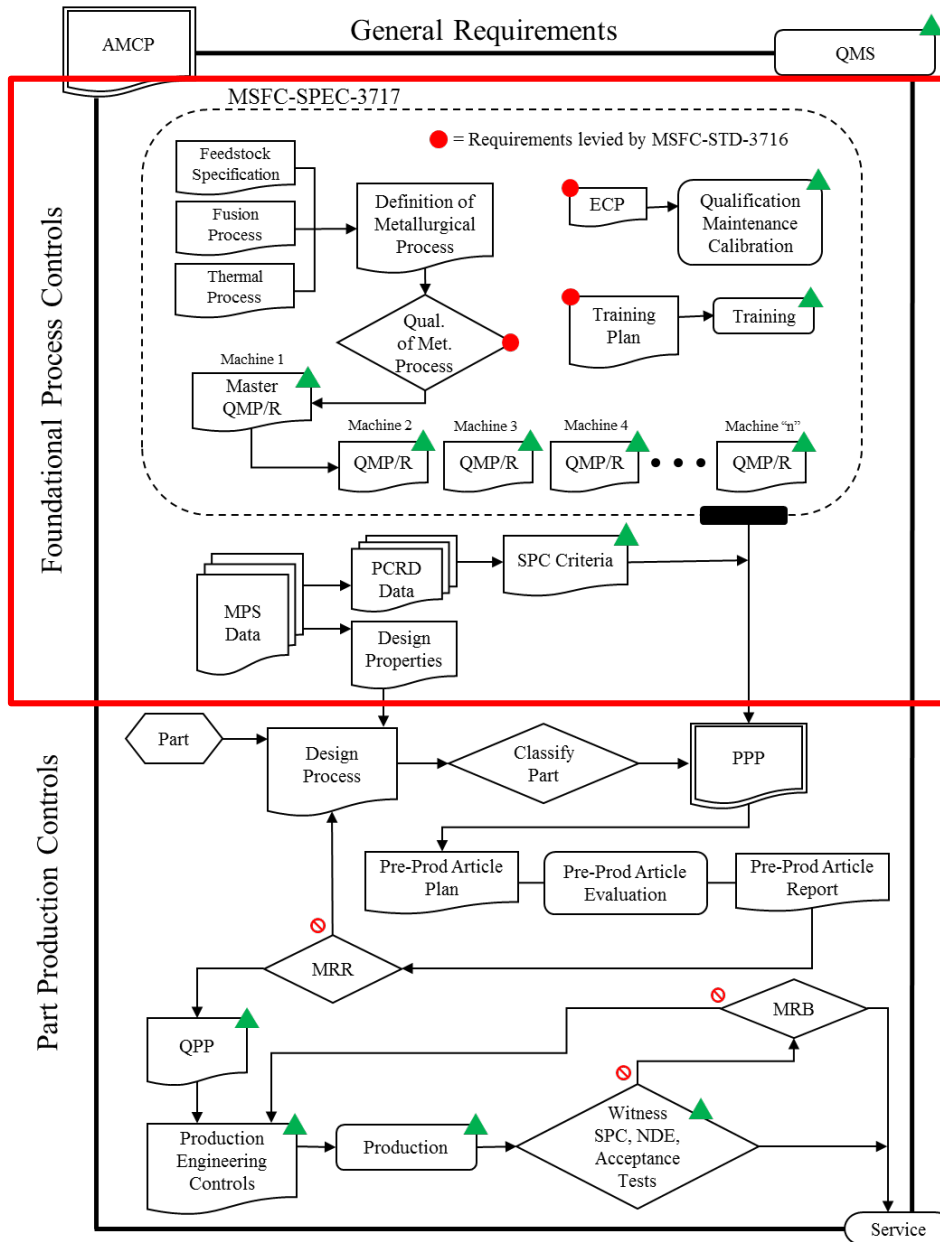
DRAFT 1 – April 10, 2017

This official draft has not been approved and is subject to modification.  
DO NOT USE PRIOR TO APPROVAL

CHECK THE MASTER LIST — VERIFY THAT THIS IS THE CORRECT VERSION BEFORE USE

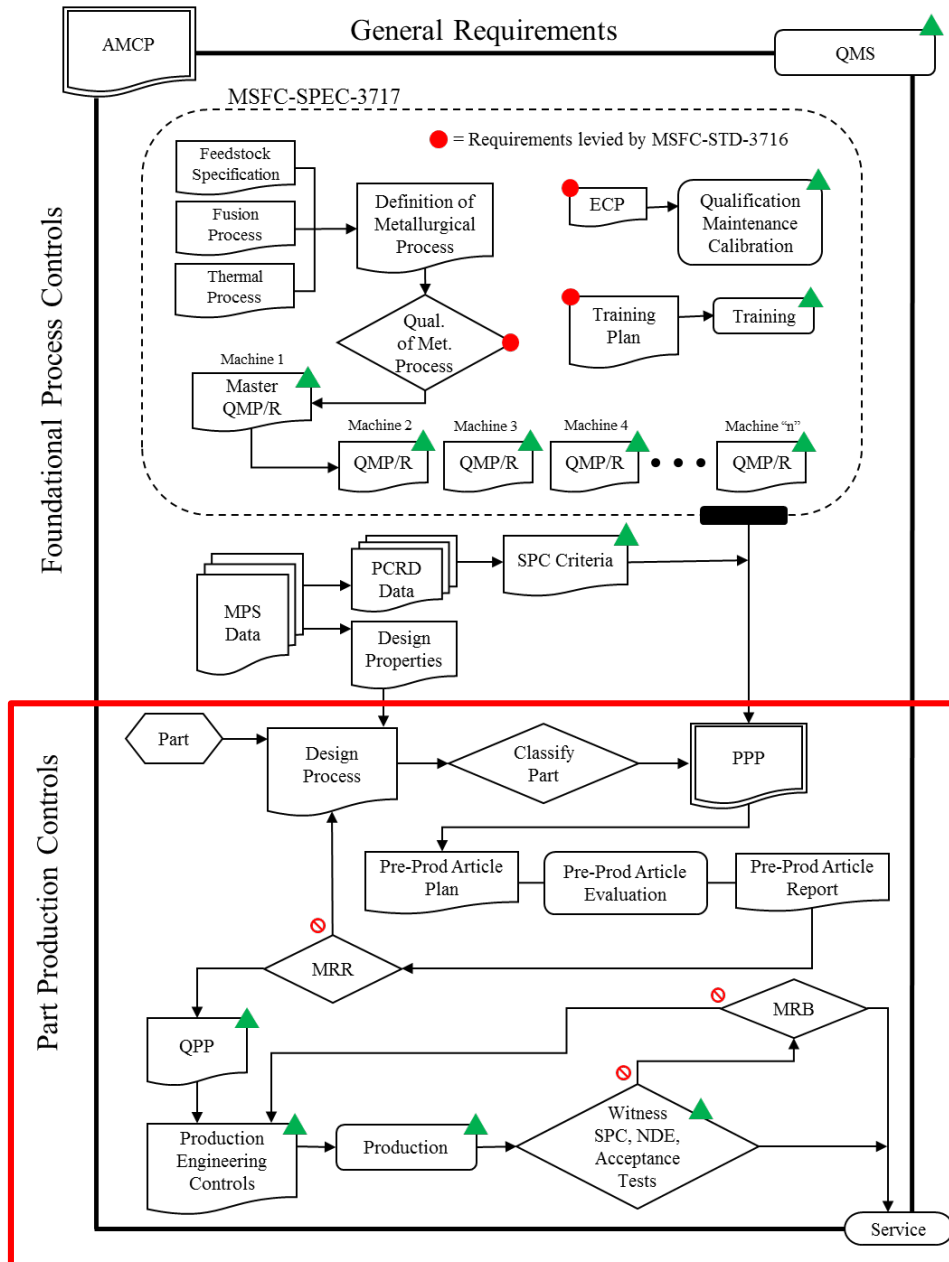
**THIS STANDARD HAS NOT BEEN REVIEWED FOR EXPORT CONTROL RESTRICTIONS**  
**DRAFT VERSIONS DISTRIBUTED FOR REVIEW ARE NOT TO BE DISSEMINATED**

- MSFC-STD-3716; Standard for Additively Manufactured Spaceflight Hardware by Laser Powder Bed Fusion in Metals
- MSFC-SPEC-3717: Specification for Control and Qualification of Laser Powder Bed Fusion Metallurgical Processes
- Documents are currently under review by the MSFC Control Board for official release.
- Framework may be tailored for other AM processes.

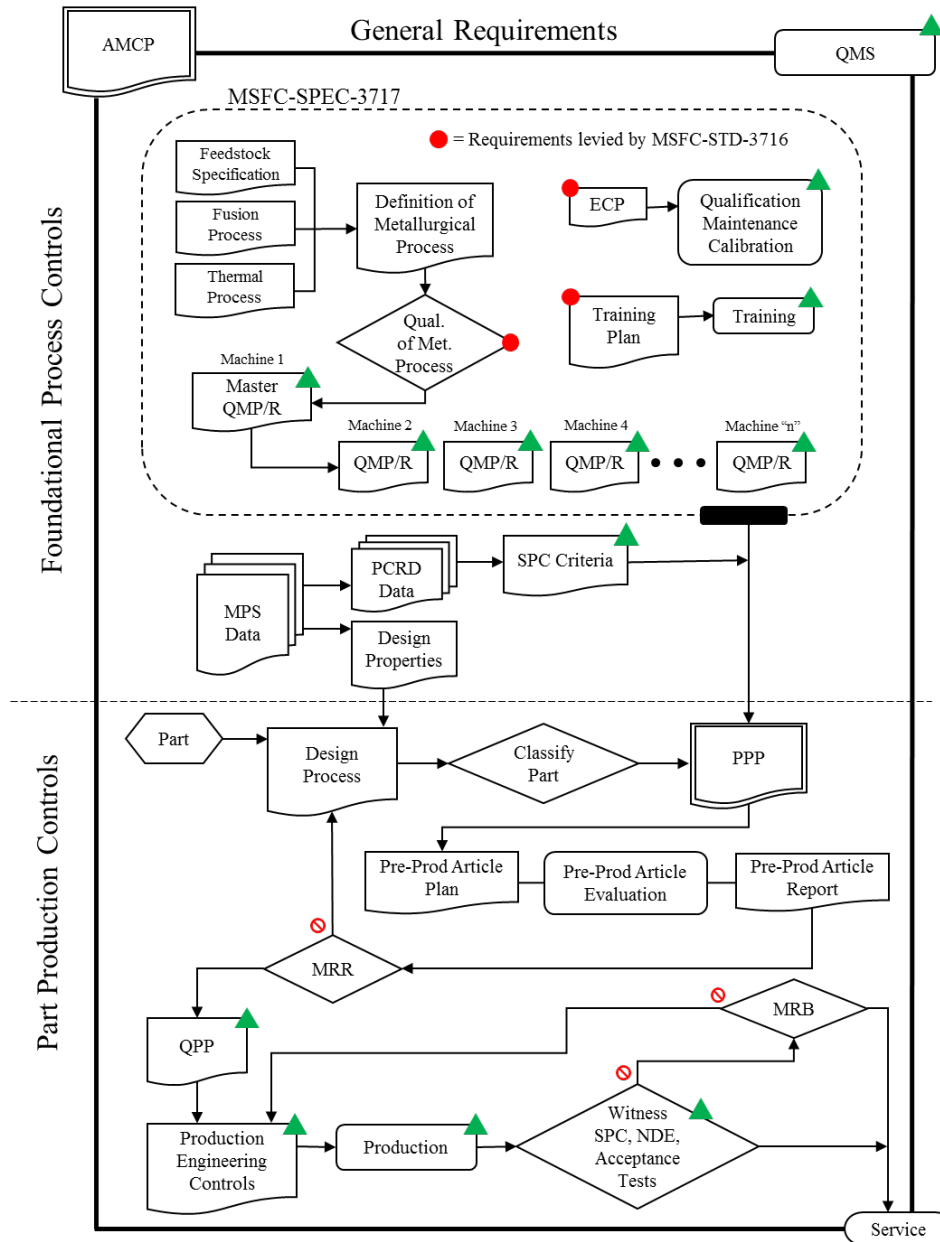


- Foundational controls provide the basis for the production of quality AM hardware.
- **MSFC-SPEC-3717** provides requirements for **control and qualification of processes**.





- Part Production Controls employ the foundational controls and classic engineering processes to produce quality AM hardware.
- **MSFC-STD-3716** provides requirements for
  - AM design process
  - Part classification
  - Part production plans
  - Pre-production articles
  - Manufacturing readiness reviews
  - Qualified Part Process
  - Production Engineering Controls
  - Acceptance procedures



- Quality Assurance is integrated throughout the standard and specification.
- ▲ symbols represent key areas of integration with quality assurance and the QMS.



## **To ensure reliable mechanical performance of AM flight hardware**

- Thorough understanding and control of the AM process is required.
  - As would be expected from a mill, foundry, or manufacturing house
- Sufficient process standardization is necessary to routinely produce quality parts.
- A robust Quality Management System and active Quality engagement is essential.
- Process controls must be demonstrated and maintained.
  - Start with a solid foundation
    - Qualified metallurgical process and material property database
  - Ensure mechanical reliability
    - Process witnessing, statistical evaluations
- All AM flight hardware requires standard acceptance procedures.
  - NDE
  - Proof testing

NASA-developed qualification methodology and requirements are available as guidance.